

Detailed Mesometeorological Studies of Air Pollution Dispersion in the Chicago Lake Breeze¹

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ABSTRACT—The lake-breeze circulation on the Great Lakes is often as vigorous as its oceanic counterpart. This paper shows that lake breezes frequently exert drastic control on mesoscale air pollution patterns in urbanized shoreline areas, in this case, Chicago, Ill. Observational data were gathered from a surface mesonet, surface and satellite cloud photography, a chain of pilot balloons normal to the shore, optically tracked constant-level balloons, and aircraft measurements of suspended particulate concentrations in several size ranges. On the 2 late summer days studied, the lake breezes were extremely well developed. Inflow depths ranged from 500 to 1000 m, with peak inflow velocities of 6–7 m/s. Beginning at the shoreline between 0800 and 0900 LST, the breezes penetrated inland over 40 km. Clearly defined return flow layers were present both days. Eulerian wind field measurements from serial pilot balloon releases were used to make cross sections of the u wind component. Computed one-dimensional divergence values defined the approximate u , w streamline patterns with time. Convergence values in a narrow (1–2 km) zone at the lake-breeze front exceeded $200 \times 10^{-5} \text{ s}^{-1}$, and calculated upward motions reached 125 cm/s. Optically

tracked tetroons yielded Lagrangian trajectory data that confirmed the basic pattern. Most importantly, the tetroons recirculated within the lake-breeze cell, describing a helical trajectory roughly centered on the shoreline. This strongly suggests that air pollutants will likewise be at least partially recirculated over the shoreline, accumulating to levels higher than would otherwise be expected.

An NCAR Queen Air instrumented aircraft took continuous cross sections of particulate concentrations and temperature through the lake-breeze life cycle. The smaller suspended particulates (0.5–3.0 μm), which essentially float with the air, clearly suggest that a significant fraction of the pollutants released from nearshore sources move inland within the inflow, rise aloft at the front, advect lakeward in the return flow layer, and then sink back down into the inflow layer offshore. By contrast, larger particles (7–9 μm), having significant terminal velocities, fall out of the cell while over the lake and do not appear to take part in the recirculation phenomena. The role of continuous fumigation of plumes from elevated point sources is also discussed. A schematic model of the lake breeze and its effects on pollutant transport is presented.

1. INTRODUCTION

Lake breezes, which on the Great Lakes are nearly as well developed as their oceanic counterparts, have received notice in American scientific literature as far back as 1799 (Ellicott 1799). Hazen (1893) documented their effect upon the climate of Chicago, Ill. In the last few years, however, it has become apparent that, from the viewpoint of the air pollution meteorologist, these fresh, cooling winds represent a mesoscale regime frequently associated with localized but serious air pollution hazards. Hewson and Olsson (1967) presented a qualitative discussion of the deleterious effects of the Great Lakes on air quality levels. This paper is a detailed case study that further specifies and illustrates the problems faced in urbanized areas on the shores of these lakes, where over a quarter of the nation's population resides. In particular, this paper will note the effects of the intense inversions produced by the relatively cold lake waters during spring and summer and the partial recirculation of pollutants within the lake-breeze cell allowing for the buildup of high concentrations of pollutants in spite of apparently good ventilation.

Bellaire (1965) was the first to use ship-towed wiresondes to measure the extremely intense inversions found over the Lakes. Lyons (1970) further studied Bellaire's data and developed a numerical simulation scheme to model these conduction inversions, which are shallow (less than 150 m) but which sometimes approach 30°C in intensity. Figure 1 shows the results of a wiresonde run from the western to eastern shore of Lake Michigan on June 3, 1966, a day on which southwest winds advected across the lake with water temperatures largely less than 8°C. While inland high temperatures approached 30°C that afternoon, the advecting warm air mass was cooled rapidly to almost that of the lake water. Note the rapid remodification, however, on the lee (eastern) shore as determined by micrometeorological tower data (fig. 1).

Table 1, showing mean lake surface temperatures (Church 1945) versus average air temperatures observed at a site sufficiently far inland to be largely unaffected by the lake, illustrates the extreme air-water contrasts that can develop, especially during the month of May. Such inversions are always present over the lake during days of strong cross-lake wind flow or when lake-breeze circulation cells are present. A spectacular manifestation of the stability of overlake air is provided by a view of a smoke

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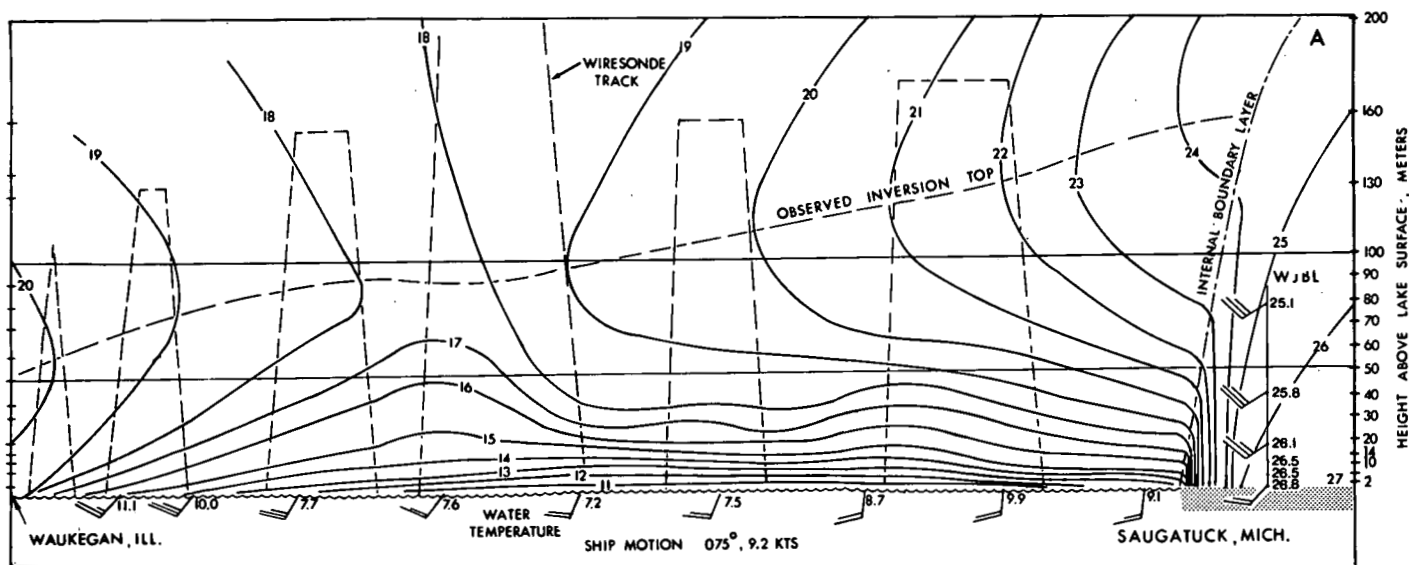


FIGURE 1.—June 3, 1966, temperatures ($^{\circ}\text{C}$) measured by a tethered wiresonde towed by the University of Michigan vessel, R/V *Mysis*. The winds observed at deck level (one barb equals 5 kt in all illustrations) and surface water temperature are also plotted. The ship left the west shore of Lake Michigan at 0800 CST and arrived at the east shore, a distance of 160 km, at 1615 CST.

TABLE 1.—Smoothed values of mean water surface temperature ($^{\circ}\text{F}$) over the southern basin of Lake Michigan and air temperature readings taken at Argonne National Laboratory, 40 km southwest of Chicago

Month	May				June				July				August			
	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
Week																
Temperature																
Maximum obs.	92	92	93	94	94	95	96	97	98	97	95	94	94	93	93	92
Average max.	72	75	77	78	79	80	80	81	82	82	82	81	79	78	77	76
Average min.	51	53	56	58	59	60	61	62	63	63	63	61	60	59	58	56
Mean lake sfc.	38	39	40	43	47	50	53	57	63	65	67	70	71	72	70	69

plume from a ship, layering out for more than 50 km behind its source with virtually no vertical diffusion apparent (fig. 2).

Lyons and Cole (1973) studied one serious aspect of the onshore flow of this stabilized air mass on sunny days. High-level plumes from such sources as shoreline power plants undergo continuous fumigation at a point several kilometers inland for hours at a time resulting in remarkably high surface concentrations of pollutants. This effect will occur even without the presence of a lake breeze, such as when gradient easterly flow is affecting cities on the western shore of Lake Michigan. These conduction inversions, while intense, are eliminated after 10–30 km of inland fetch due to strong heating from the ground below. Since the only radiosonde station in the Lake Michigan area, Green Bay, Wis., is about 45 km from the lake, it is not surprising that Holzworth's (1972) mixing depth climatology study failed to show a significant effect on the Great Lakes. Using his charts, we should find summertime afternoon mixing depths to be in the 1300-to 1600-m class in the Milwaukee-Chicago area. On more than 50 percent of all warm season days, however, when easterly flow prevails at the shoreline where both industry and population are concentrated, values of perhaps 10 to 20 percent of that are more probable.

Intense inversions, however, if known to occur, are relatively tractable in terms of computing air quality levels. If area pollution forecasts are to be made using a computer and employing the typical steady-state Gaussian plume assumptions, an intensely stable layer present over a region does not impose a serious computational difficulty over and above those associated with this type of model. But if a lake breeze occurs within the air quality control region, then the entire picture changes. Figure 3 shows the plume from a shoreline power plant located 20 mi south of Milwaukee, Wis., having four stacks varying in height from 75 to 170 m above the lake.³ Smoke (as well as gaseous pollutants) from the lower stacks are drifting inland within a shallow lake breeze while that from the highest stack manages to penetrate into the westerly return flow current aloft. And as this paper will show, the high-level plume will not merely drift out over the lake away from the populous shoreline, but will at least partially subside into the lake breeze inflow layer offshore only to affect inland regions at a slightly later time. Clearly, any successful numerical prediction schemes of air pollution potential in Great Lakes cities will have to contend with this and other phenomena to be discussed later.

³ This plant has subsequently installed electrostatic precipitators to largely eliminate its particulate emissions.

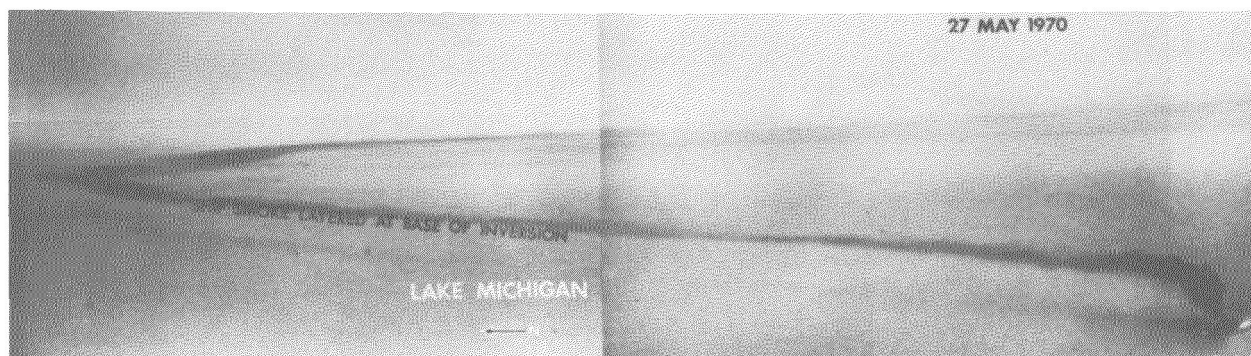


FIGURE 2.—Photograph of a lake steamer approaching Milwaukee harbor at 1520 cst, May 27, 1970, taken from an altitude of 1000 m above the lake. The ship was executing a broad turn resulting in the unusual shape to its smoke plume, which extended all the way to the horizon.



FIGURE 3.—Smoke from a power plant 30 km south of Milwaukee at 1500 cst, Mar. 13, 1970, during a shallow lake breeze. Smoke from lower stack (165 m above lake level) is partially trapped in the inflow while part escapes into the return flow layer and spreads out over the lake to the east (right). Photograph by Tim Ondercin.

This paper will concentrate on field studies conducted in the Chicago area on Aug. 12 and 13, 1967. These two days had exceptionally well-developed lake breezes. A complete climatology of the Chicago lake breeze is presented by Lyons (1972), but the following summary here places this study in proper context. True lake breezes occur at the Chicago lakefront approximately 35 percent of all days during May through August, although they are observed often in March, April, and September, and, on rare occasions, even in January and February. They typically push onshore between 0800 and 0900 cst. The inflow layer averages about 500 m in depth, but can range from 100 m to over 1000 m. The characteristic

that delineates a lake breeze from gradient onshore flow is the presence of a return flow layer aloft, typically about twice the depth and half the peak speeds found in the inflow. In addition, a distinct leading edge of the inflow, variously called the lake-breeze front, convergence zone, or wind shift line, separates air streams of land and lake origin. It may push inland anywhere from several hundred to over 40 km. Peak wind speeds generally occur in the lower portion of the inflow and reach 6 to 8 m/s. About 30–40 percent reach inland as far as Midway Airport, 15 km from the lake. The lake breeze on the eastern shore of Lake Michigan exhibits similar characteristics (Olsson et al. 1968).

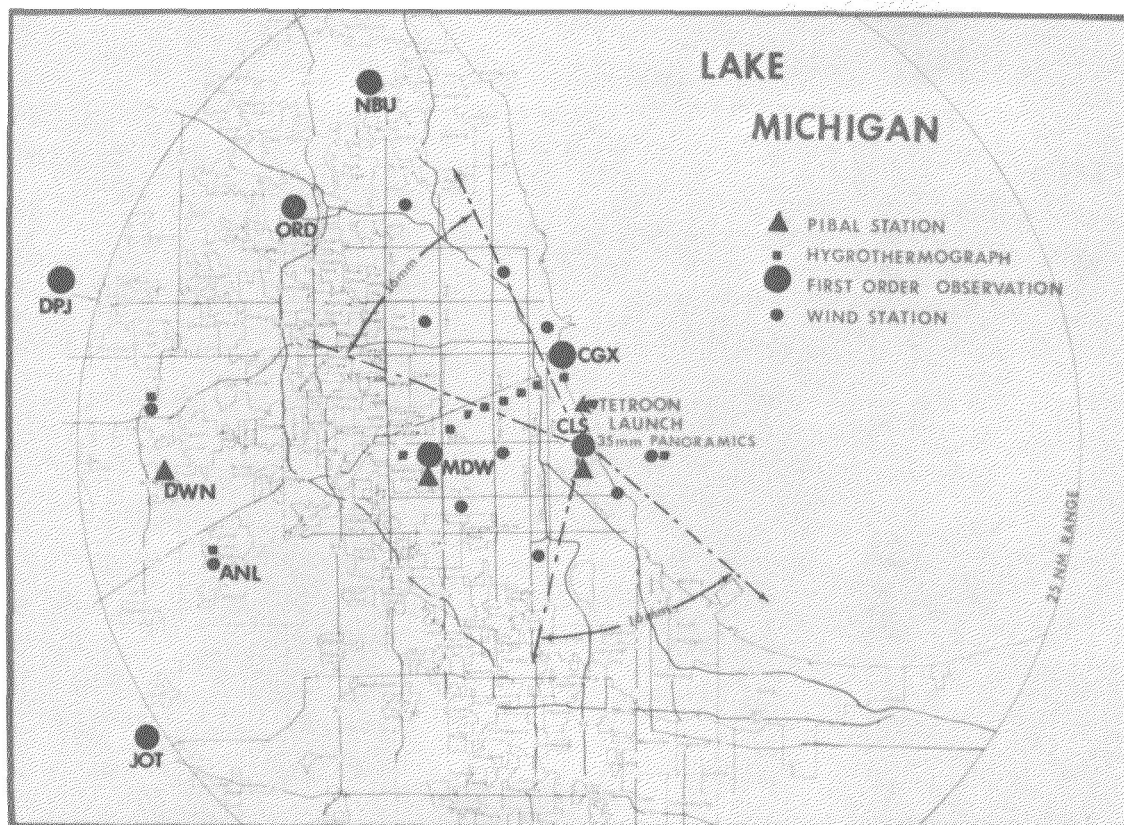


FIGURE 4.—Mesoscale data network in the Chicago metropolitan area. CLS indicates the NOAA Chicago WSR-57 radar tower on which were mounted time-lapse cameras for smoke and cloud photography, as well as one of the two theodolites used in the tetroom tracking.

2. MESOSCALE DATA NETWORK

By combining the various sources of data available in the Chicago area, we found a virtual mesonet of stations during the field program in August 1967. As shown in figure 4, there are six airport stations reporting hourly conditions within approximately 30 n.mi. of the Chicago Loop. The operations were conducted from the University of Chicago (CLS), where hourly weather records were also made. CLS is the Chicago National Weather Service WSR-57 radar tower, less than 1 km from the lakeshore. On this tower, 16-mm time-lapse cameras were used to monitor smoke and cloud patterns, and 35-mm hand-held cameras recorded hourly 360° panoramic views. Surface wind data were augmented by the use of the City of Chicago, Department of Environmental Control's Telemetered Air Pollution (TAM) Network, which provided eight sites reporting wind velocities, as well as sulfur dioxide concentrations, at 15-min. intervals. The surface temperature field was further delineated by using a chain of eight hygrothermographs stretching from the Loop southwestward to a point just west of Midway Airport (MDW). Single theodolite wind soundings were made at three sites; CLS (1 km from the shoreline), MDW (15 km inland), and DWN (Downers Grove, Ill., 37 km inland). Hourly pibals from about sunrise to sunset allowed the rough determination of the Eulerian wind field. Super-pressure balloons (tetroons) were launched from a site at the shoreline near CLS. Tracked by optical theodolites,

these provided a useful Lagrangian tracer of air motions within the lake breeze. The tetroon operations were under the direction of the University of Michigan. The National Center for Atmospheric Research (NCAR) supplied a fully instrumented twin engine Queen Air aircraft that measured, among other things, temperature, dewpoint, and aerosol concentrations over several size ranges with an optical counting system. A 50-m micrometeorological tower was also available at Argonne National Laboratory (ANL) at a site well inland from the lake. With the addition of standard satellite and radar data, a complete mesoscale picture of the lake breeze and its associated phenomena could be determined.

Fortunately, the topography of the area is extremely flat with no more than about 100 m of relief to be found throughout the region. The shoreline is gently curving at the southern end of the lake, and for the purposes of this study the Chicago shoreline is assumed to be oriented 330°–150°.

3. GENERAL CHARACTERISTICS OF THE LAKE BREEZE

The synoptic pattern on Aug. 12 and 13, 1967 was relatively static. A large, cool continental polar high-pressure system dominated the Great Lakes. On August 12, the center was located west of Lake Michigan (fig. 5); by the 13th, it had shifted slightly to the east of the lake. Clear skies and light winds allowed for near-record low

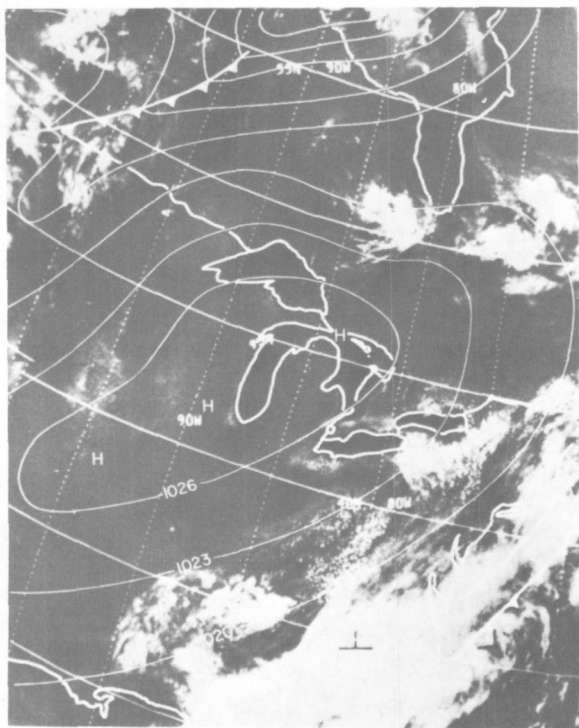


FIGURE 5.—Synoptic situation at 0600 CST, Aug. 12, 1967, superimposed on a satellite photograph taken at 1400 CST.

temperatures in many areas. Figure 6 is a plot of 0600 CST temperatures and winds on August 12. Temperatures were generally in the 40s, except where notably warmer in the urban heat islands such as Chicago, Muskegon, Mich., etc. The lake had warmed to approximately 70°F over the southern basin, with narrow bands of colder upwelling water along both shorelines. Thus, the lake was markedly warmer than the land at sunrise, and the expected land breezes were in progress, as evidenced by the offshore winds recorded at all coastal stations.

The same conditions prevailed on the morning of August 13; pollutants near the surface west of Chicago drifted toward the lake in the shallow land-breeze outflow while dense smoke was present aloft in the very light northeasterly flow, which had collected pollutants from the Chicago area (fig. 7). The land-breeze outflow layer was only 150–300 m in depth. The lake breezes pushed onshore both days between 0800 and 0900 CST. As shown in figures 8A and 8B, the wind shift line or convergence zone penetrated far inland, over 40 km on August 12 and slightly less on August 13 due to a strengthening southwesterly surface flow as the anticyclone ridge pushed to the east.

As is typical of lake breezes, the convergence zone maintained itself roughly parallel to the shoreline as it moved inland. Selected hygrothermograph traces (figs. 8A, 8B) show that when the lake breeze passes a given point (arrow), the temperature either falls slightly or generally levels off. Depending on whether or not the air mass as a whole has surface dew points lower or higher than the lake surface water temperature, the lake air may be moistened or dessicated. Thus, humidity may either

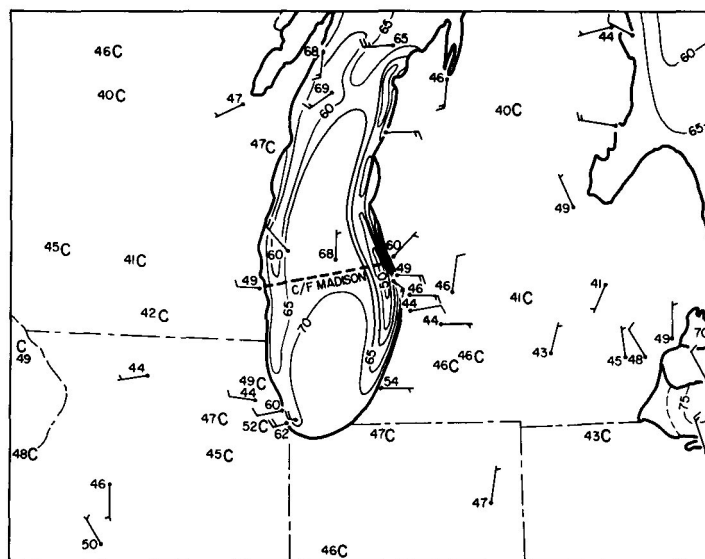


FIGURE 6.—Surface temperatures and winds at 0600 CST, Aug. 12, 1967. Also, 5°F surface water isotherms are drawn. C indicates calm.

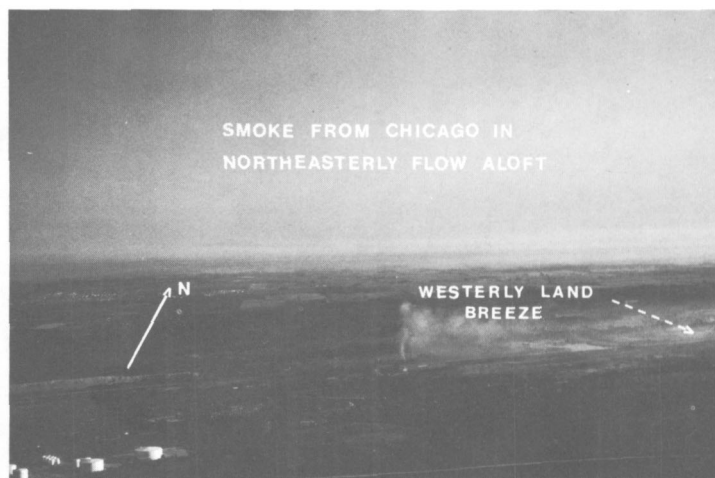


FIGURE 7.—Photograph taken from an NCAR Queen Air aircraft at 0700 CST, Aug. 13, 1967, from 300 m AGL, 35 km west of CLS, looking north.

drop or rise somewhat (as is the case here) with the penetration of the lake air to a station.

Figures 9 and 10, 360° panoramic views from the CLS tower, reveal the cloud patterns associated with the lake-breeze convergence zone on both days. On August 12, the air mass was relatively unstable, and cumulus convection over land was fairly vigorous. The first clouds formed directly over the lake-breeze convergence line about 2 km inland about 0830 CST. The cloud line, which marked the inland penetration of the cooler air, pushed rapidly inland during the day and could not be seen from the shoreline after about 1400 CST. These photos, taken with smoke-penetrating infrared film, also show that cumulus were forming directly over the steel mills on the southeastern side of the city. An almost continuous cloud was seen developing out of the steel mill plume throughout the morning hours, pushing slowly inland with time as the strengthening easterly surface flow caused increasingly

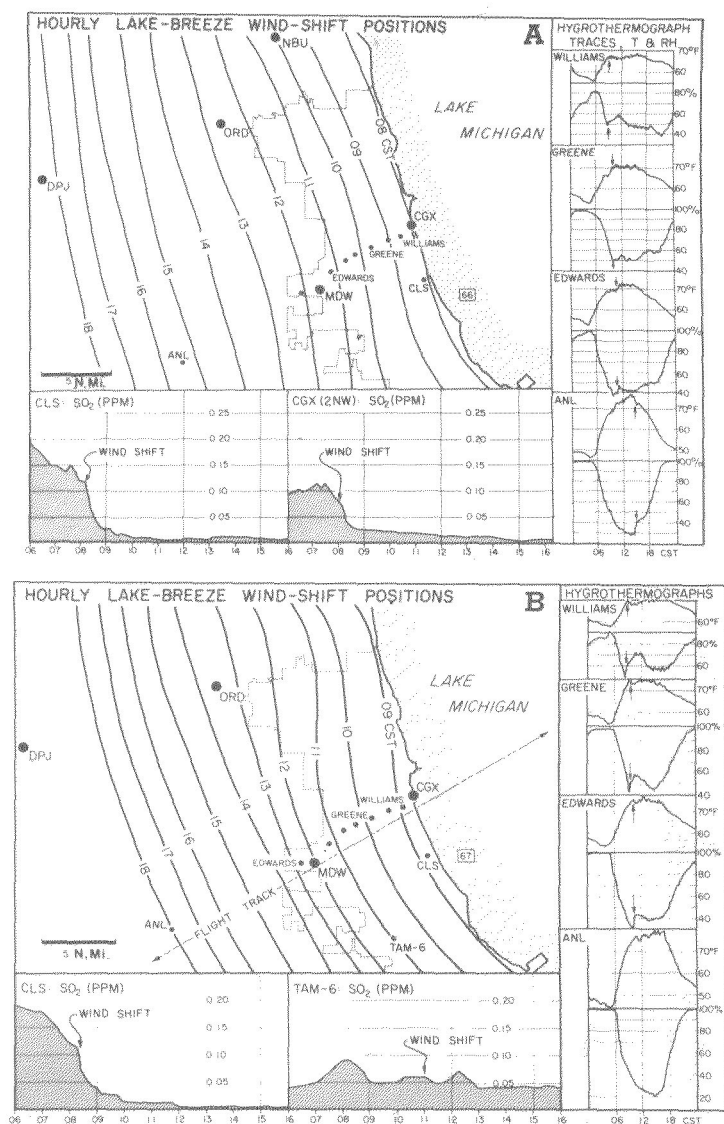


FIGURE 8.—Hourly positions (csr) of the lake-breeze front on (A) Aug. 12, and (B) Aug. 13, 1967. Hygrothermograph traces from several sites reveal typical lake-breeze patterns (arrow marks wind shift). Sulfur dioxide readings from two sites likewise show typical response (readings in parts per million). Water temperature ($^{\circ}\text{F}$) is indicated in box offshore.

greater slope to the plume axis. Another most interesting feature was that, as commonly occurs, the lake-breeze convergence zone was marked by a towering wall of smoke. Color time-lapse movies clearly showed that the smoke rose in the convergence zone updrafts, was injected directly into the lake-breeze frontal clouds, and largely disappeared—probably due to the scavenging effects of the cloud droplets on the smoke particles. Also visible on the left side (east) of figure 9 are well-developed cumulus clouds over the lake, approximately 20 km offshore.

It should be remembered that very cold air had drained out over the lake during the night in the land breeze, and, with the 70°F lake water, a situation analogous to wintertime convection over the lake was present. This convection remained active until approximately 1030 CST when the clouds suddenly began to become disorganized and disintegrate. It is suspected that the lake-breeze

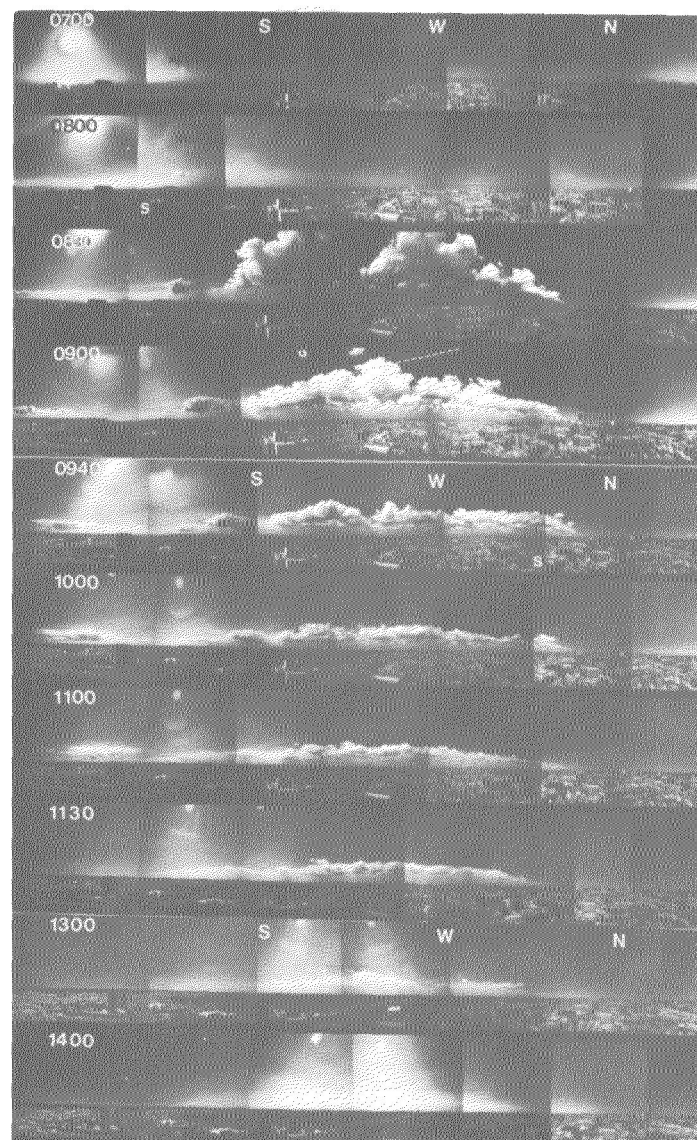


FIGURE 9.—Full 360° horizon panoramic photographs of cloud and smoke patterns, Aug. 12, 1967, taken from CLS (0700–1400 cst).

circulation cell formed over the shoreline and spread inland and offshore at roughly the same rates. A zone of suspected strong divergence and subsidence associated with the lakeward edge of the lake-breeze cell probably reached the overwater clouds around 1000-1100 CST and caused their rapid demise.

On August 13, the cumulus activity was considerably suppressed due to a strengthening of the synoptic scale subsidence inversion in the area. A ragged line of cumulus clouds associated with the lake-breeze convergence zone pushed inland during the day and out of sight of the shoreline by 1500 cst (fig. 10). The cumulus on this day also formed directly over the wall of smoke marking the convergence zone; and likewise over the larger steel mill complexes during the morning. Only poorly developed cumulus clouds, however, were seen over the lake, around 0700 cst, probably the result of higher minimum temperatures the previous night. From an aircraft at 3000 m MSL, 20 km east of CGX at 0930 on August 13, cumulus and smoke patterns were photographed (fig. 11). The

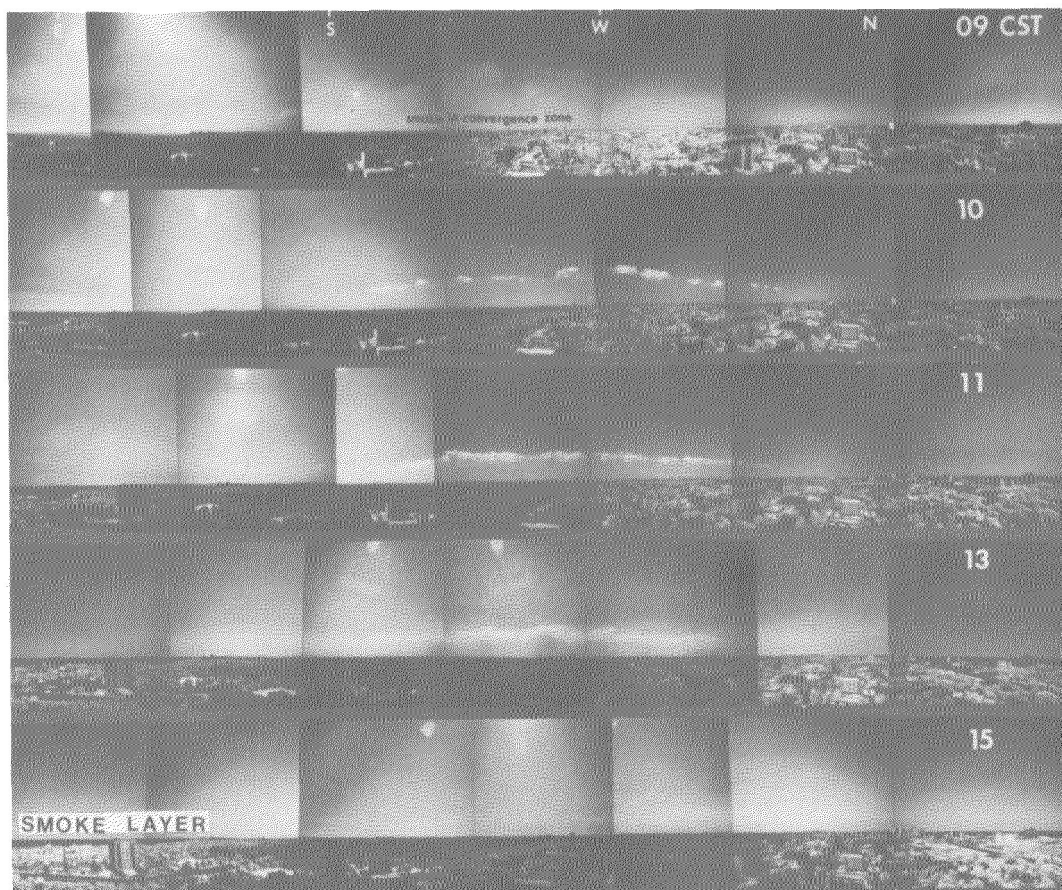


FIGURE 10.—Same as figure 9, for Aug. 13, 1967 (0900–1500 cst).

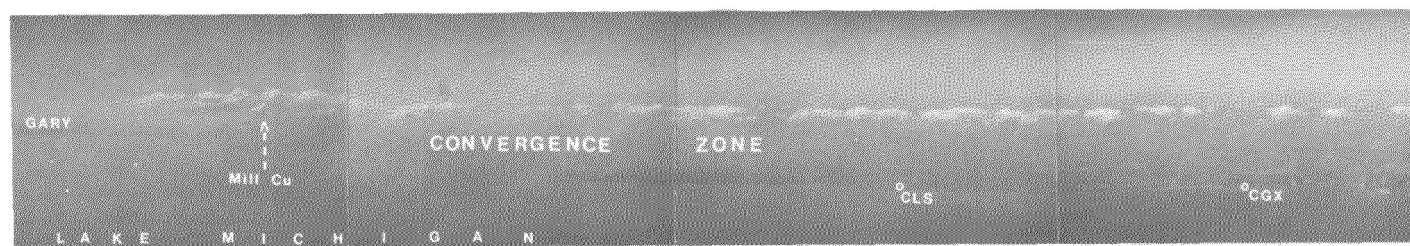


FIGURE 11.—Panoramic view of lake-breeze clouds and smoke patterns taken at 0930' cst, Aug. 13, 1967, from NCAR plane at 3000m MSL, 20 km east of CGX.

densest smoke is present over the heavily industrialized south side of Chicago and the Gary-Hammond, Ind., area. Clearly visible is a wall of smoke marking the inland penetration of the lake breeze over which the line of clouds formed.

A satellite view of the Great Lakes at 1400 cst on Aug. 12, 1967, over which aviation station reports have been superimposed, reveals that lake breezes had pushed inland around virtually the entire perimeter of the Great Lakes (fig. 12). A mesoanalysis of the Chicago area at the same time (fig. 13) shows the distinct convergence of the surface winds at the lake-breeze front. Schematically drawn in are the cumulus patterns in the area. Most importantly, however, are sketches made of the behavior of the plumes from the major steel mill complexes. The dense red smoke, observed from the aircraft offshore, drifted inland within the lake-breeze inflow, rose rapidly

on the lake side of the convergence zone and then spread out over the lake within the return flow layer aloft at approximately 900–1300 m above the surface. The wall of smoke and the steel mill plumes can be seen in figure 14. The pall of smoke in the return flow layer (which is difficult to photograph from this angle) was spreading north-eastward above the lake towards the observers in the aircraft.

4. EULERIAN WIND FIELDS—USING PIBALS

Hourly single theodolite pilot balloon (pibal) observations were taken at CLS, MDW, and DWN, from 0700 to 1600 cst on both days. The 30-g helium-filled balloons were tracked at 30-s intervals with 0.1° resolution in azimuth and elevation angles. Data were processed by computer, yielding the mean wind speeds in 100-m thick

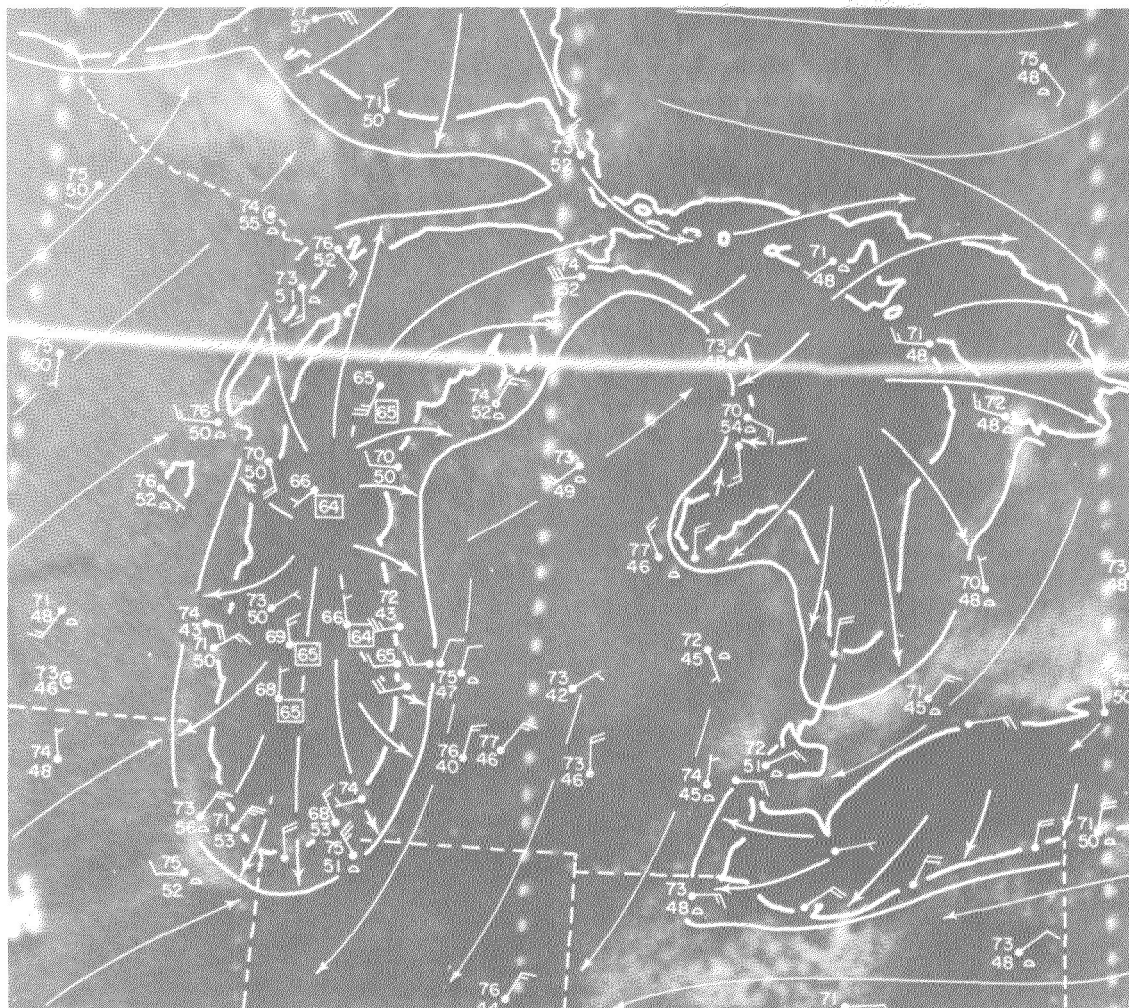


FIGURE 12.—Portion of ESSA 5 satellite photograph of the Great Lakes at 1400 cst, Aug. 12, 1967, with surface data and streamlines drawn in. Water temperatures ($^{\circ}\text{F}$) are shown in boxes. Heavy line marks the inland penetration of the lake-breeze inflow.

layers. The wind vectors were further broken down into u (normal to shore) and v (parallel to shore) components. Figure 15 shows a time section of the u component of the wind at the three stations on August 13. At the shoreline (CLS), the land breeze before 0800 cst was approximately 200- to 300-m deep with a peak velocity of about 2 m/s with a weak onshore flow layer above it. The onset of the lake breeze occurred at 0800 cst and maintained an inflow depth of about 500 m throughout the day. The peak inflow velocity of 6–7 m/s occurred at 1500 cst about 200 m above the surface. The deep return flow layer aloft likewise reached maximum intensity of 5 m/s around 1100 m above ground level (AGL) at the same time. Farther inland at Midway Airport (MDW), light westerly surface winds were present until just before noon, when the lake breeze hit. There appeared to be some pulsing of the lake breeze at around 1300 cst, but it quickly reestablished itself by midafternoon. At the site farthest inland, Downer's Grove (DWN), where the lake breeze did not reach until almost sunset, the winds remained light and variable throughout the day with no obvious structure.

More revealing, perhaps, are space sections of the u component of the wind at various times during the life

cycle of the lake breeze (figs. 16A, 16B). On August 12 (fig. 16A) at 0900 cst, the lake breeze apparently began directly over the shoreline with an initial inflow layer almost 1000 m in depth—somewhat larger than typical. Although the 0900 cst pibal at CLS had already detected a well-established lake-breeze inflow, the wind recorder at the offshore water crib (about 5 km offshore) still recorded a westerly wind. This would suggest that the lake-breeze cell formed directly over the shoreline and spread both inland and offshore. The lake-breeze inflow layer maintained a depth between 700 and 800 m through the remainder of the day and likewise exhibited a peak u component of inflow of about 6 m/s during midafternoon at the 200-m level above the shoreline. The depth of the return flow on August 12 was constrained by the light synoptic scale northeast winds aloft; it extended only up to about 1300 or 1400 m. Figure 16B shows similar data for August 13, with the location of the clouds above the convection zone indicated. There is obviously a degree of subjectivity attached to these analyses, inasmuch as no over-water pibal data exist and there are only three land stations. However, the hour to hour continuity of pibal soundings at each station suggests that the flow can

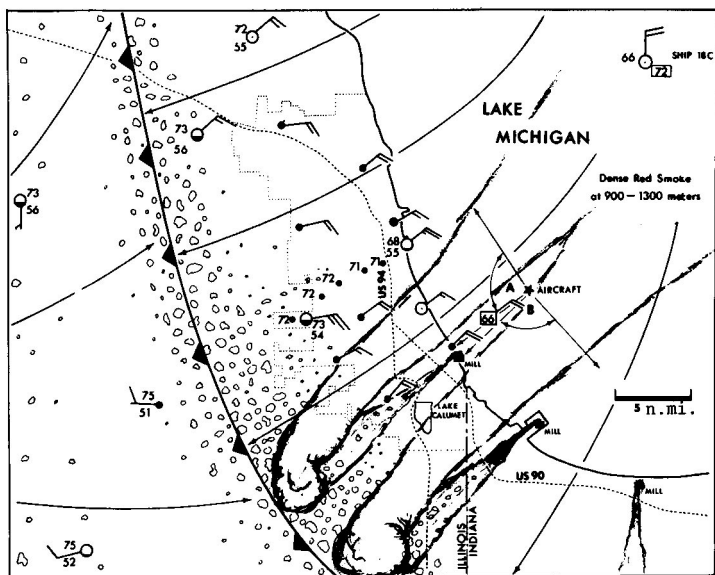


FIGURE 13.—Surface mesoanalysis of lake breeze in Chicago at 1400 CST, Aug. 12, 1967, showing surface wind streamlines and position of lake-breeze wind shift line (barbs). The approximate outlines of major steel mill plumes are indicated. The cumulus associated with the lake-breeze front are sketched.



FIGURE 14.—Photograph of smoke and clouds taken from spotter aircraft, view as indicated in figure 13.

be reasonably well determined, at least over land, by this density of stations. An increase in pibal stations to six or even 10, might reveal more detailed information about the lake-breeze cell, but the basic structure should probably stay the same.

Since these data show that the inflow velocities are greater than the inland penetration speed of the front, C , there must be convergence and vertical motion in the overland portion of the cell. There are relatively few reports in the literature, however, of actual observations of the vertical component of the lake breeze. By using the continuity equation, one can compute vertical motions from data such as those shown in figure 16A. One assumption must be made, however; mainly, that there is very little variation in the wind in the parallel-shore direction, (i.e., $\partial v / \partial y = 0$). This was suggested in the study of Moroz (1967). Thus, the divergence can be calculated using only

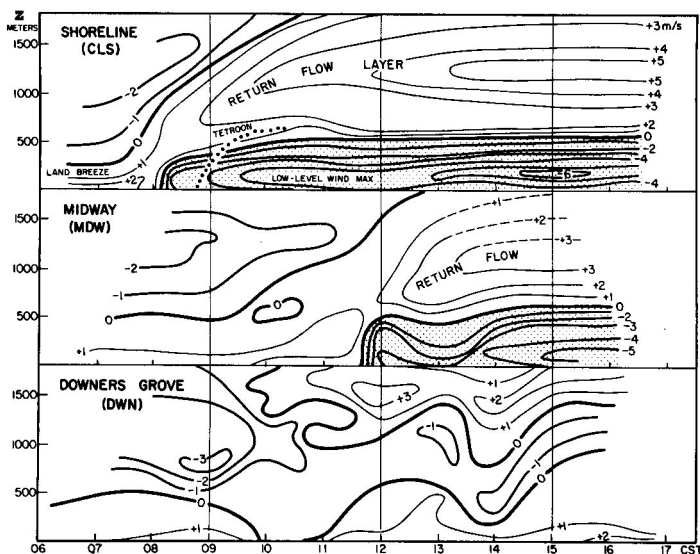


FIGURE 15.—Time sections of u component (m/s) of lake breeze observed at CLS, MDW, and DWN, 0700-1600 CST, Aug. 13, 1967. Heavy line marks $u=0$ isogon; lake-breeze inflow is stippled.

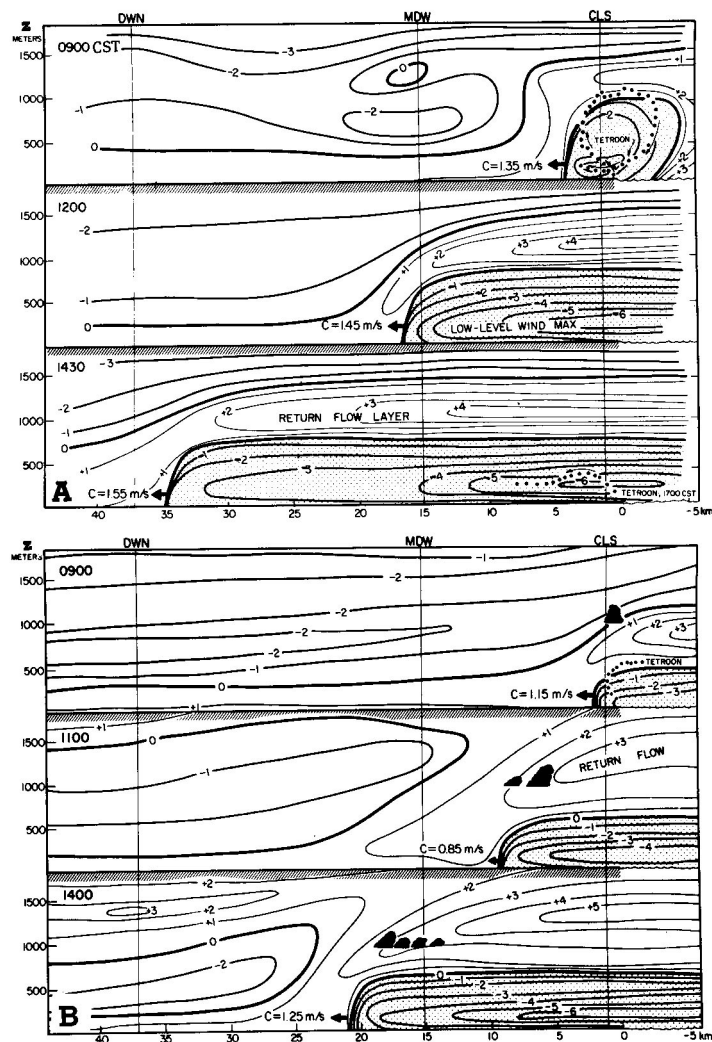


FIGURE 16.—Cross section of the normal-to-shore of (u) component of the wind (m/s) through the lake breeze of (A) Aug. 12, and (B) Aug. 13, 1973, in Chicago at three times (CST). The approximate tracks of tetrons launched from the shoreline are plotted. C denotes the inland penetration speed (m/s) of the lake-breeze front. In (B), clouds associated with the front are indicated.

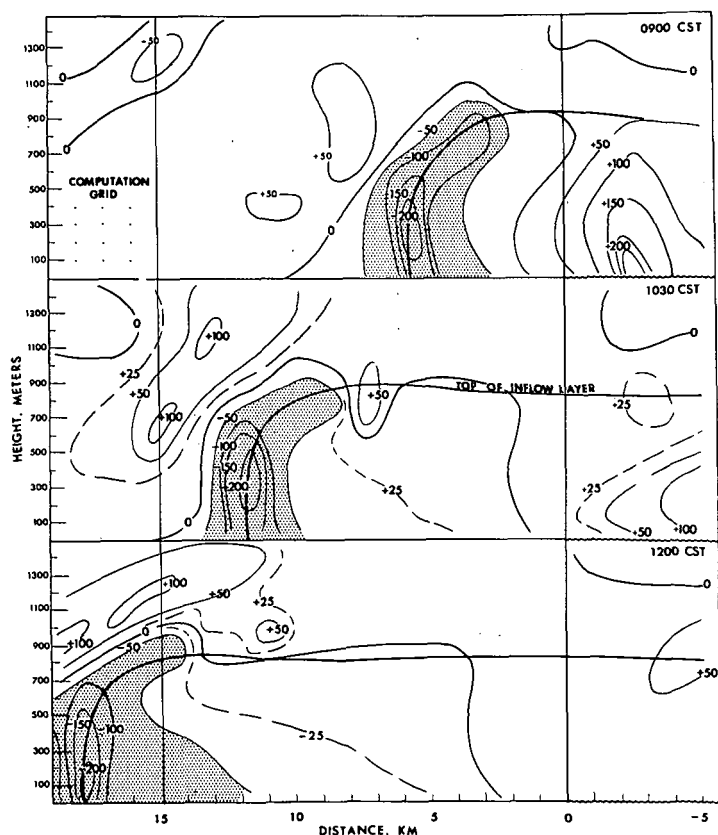


FIGURE 17.—Divergence values (10^{-5}s^{-1}) calculated for Aug. 12, 1967, at 0900, 1030, and 1200 cst. Stipple indicates convergence values in excess of $50 \times 10^{-5}\text{s}^{-1}$.

the u component of velocity. The integrated form of the continuity equation then yields

$$w(z) = w_0 - \int_{z=0}^z \left(\frac{\partial u}{\partial x} \right) dz$$

where $w(z)$ is the vertical motion at height z , w_0 is the vertical motion at the lowest level (assumed zero for the ground), and x is the distance normal to the shore. The pibal data were plotted in cross sections similar to figure 16A for each hour, smoothed by hand, and entered into an IBM 360/50 computer.⁴ Linear interpolations were made by the machine for every 15 min on a grid of 100 m in the vertical by 1 km in the horizontal. Figure 17 shows the computed divergence patterns associated with the lake breeze at 0900, 1030, and 1200 cst on August 12. Convergence values exceeded $200 \times 10^{-5}\text{s}^{-1}$ at the wind shift line itself. Also evident is a divergence band of comparable strength associated with the offshore boundary of the cell. The computed maximum values of w at the lake-breeze front increased from about 105 cm/s at 0900 cst to over 130 cm/s by 1200 cst (fig. 18). Glider pilots frequently report organized updrafts of 200 cm/s above sea-breeze fronts (Simpson 1964), so the above values would appear plausible.

Subsidence in excess of 140 cm/s was also calculated over the offshore divergence zone at 0900 cst. Although the

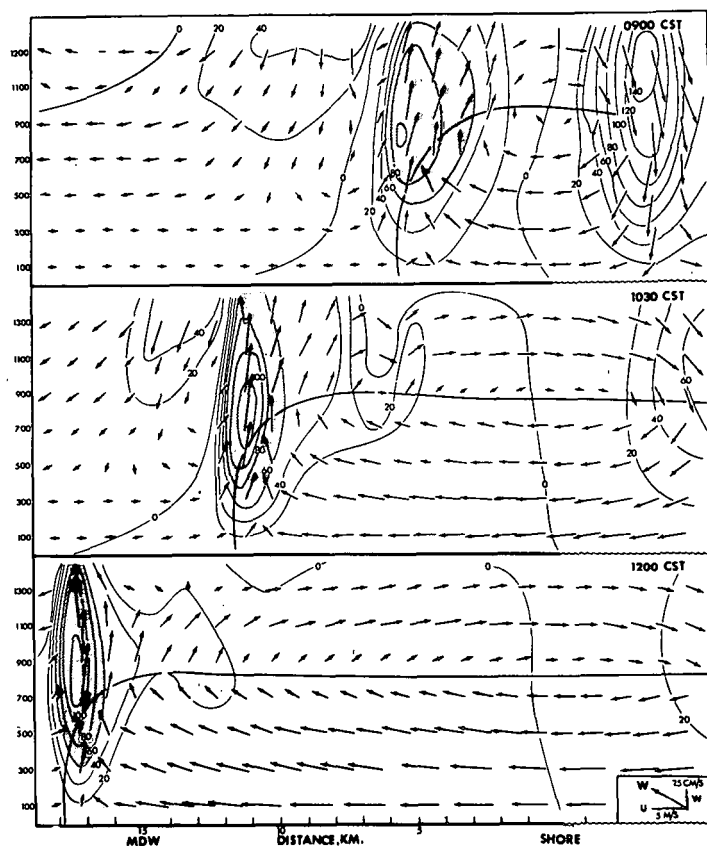


FIGURE 18.—Two-dimensional streamlines for Aug. 12, 1967, computed from data in figure 17. Isopleths of vertical motion (cm/s) are drawn; updrafts greater than 60 cm/s are shaded. Boundary of lake-breeze inflow is given by heavy line.

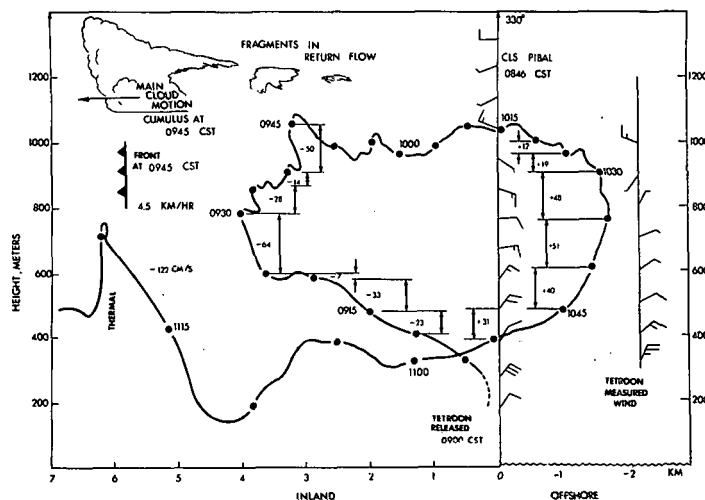


FIGURE 19.—Transverse (xz) trajectory of tetroon launched from Chicago shoreline at 0900 cst, Aug. 12, 1967. Position plotted every 5 min (dots) with mean 5-min vertical motions (cm/s) indicated (positive downward). Horizontal wind measured by tetroon as it sank just offshore is compared to actual wind sounding.

analysis over water is more speculation than a measurement, the behavior of the tetroon (sec. 5) suggests this feature to be real. Also the extremely rapid dissipation of the cumulus over the lake at 1030 cst (discussed previously) tends to confirm this particular feature in a

⁴ Mention of a commercial product does not constitute an endorsement.

qualitative sense, although the absolute magnitude of the subsidence might well be questioned.

Also shown in figure 18 are the vectorial two-dimensional streamlines from the u , w components. It is immediately seen that much of the upward motion out of the inflow layer takes place in a narrow (1-to-2-km) band above the lake-breeze front. A well-defined circulation center located above the shoreline exists throughout the period. Noteworthy is the fact that gently rising air is found at all levels in the overland portion of the cell, with subsidence restricted to over the lake.

These results appear more realistic than those obtained in some of the earlier numerical models of Estoque (1962) and Moroz (1967). In those investigations, vertical motions were computed from a horizontal grid that was too large to accurately resolve the sharp variations in u , and, therefore, w values were an order of magnitude smaller than here. Our results do compare well, however, with a more recent numerical study by McPherson (1970) who used a 4-km horizontal grid spacing and obtained patterns similar to those of figure 18. His peak values of vertical motion at times reached 60 cm/s, only about a factor of two smaller than those observed here.

5. LAGRANGIAN WIND FIELDS USING TETROONS

If the lake breeze were a steady-state system, the streamlines in figure 18 could also be interpreted as air parcel trajectories. While the generally cyclic trajectories can easily be imagined from the streamlines, their exact determination would require a time integration of fluid motions from these data. Another method of determining such trajectories; that is, with constant volume superpressured balloons, has come into use in the last decade. These balloons, sometimes called "constant-level balloons," are often used to obtain mesoscale Lagrangian air motions where Eulerian methods, such as pibal networks, would be too impractical or costly. They can also yield detailed data over water areas, appropriately called "terra incognita" by Angell et al. (1966). A popular type is the tetrahedron-shaped "tetroon," made of 2-mil DuPont Mylar, with a volume of about 1 m³. By following certain inflation procedures (Booker and Cooper 1965), one can set the tetroon to drift with the wind on a predetermined isopycnic surface. However, the high drag coefficient (0.8) and the slight expansion capability (up to 4 percent) does allow for the balloon to respond to vertical motions, behaving much like a giant molecule. The resulting buoyancy forces tending to restore the tetroon to its neutral buoyancy level once displaced do not appear to be overly strong, probably only several centimeters per second for displacements of several hundred meters. The tetroons launched for this study were nominally weighed off to float at 300 m AGL.

Many tetroon studies have been conducted using a radar-transponder system. To obtain a high resolution of the tetroon's vertical position (and, therefore, the vertical motion of the air), researchers have frequently used airplanes or helicopters to visually track the balloon. Angell

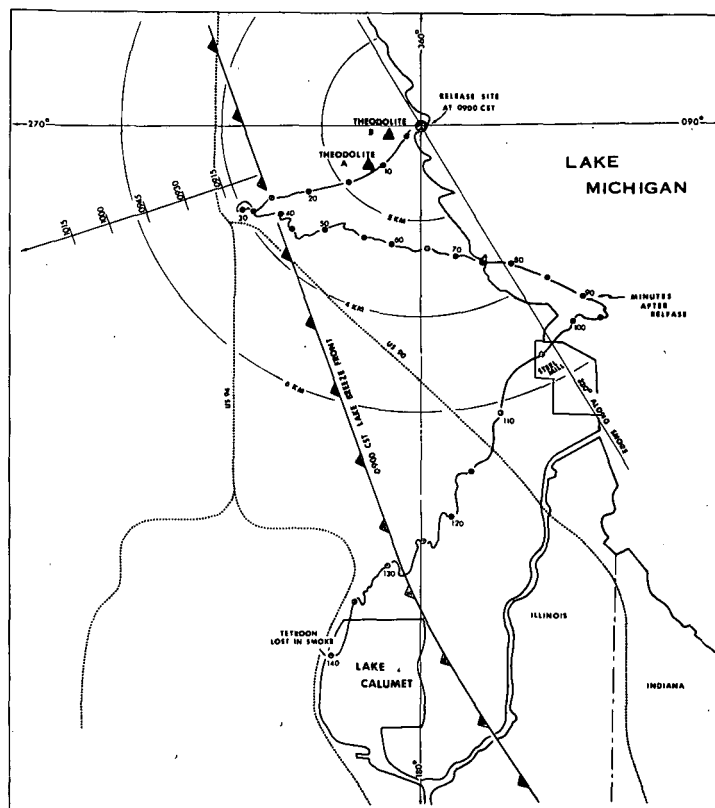


FIGURE 20.—Plan (xy) trajectory of tetroon launched from Chicago shoreline at 0900 CST, Aug. 12, 1967. Dots indicate position every 5 min. Heavy barbed line shows lake-breeze front at time of launch.

and Pack (1965), in their study of the Atlantic City sea breeze, found the WSR-57 radar inadequate to resolve the height of the tetroon. Since useful data on the lake-breeze cell could be obtained by monitoring air motions in about a 10- to 15-km radius circle, it was felt a simple and vastly less expensive system of double-theodolite tracking could be put to good use. Two 20-power standard theodolites were located atop 55-m high buildings, 680 m apart, on a 48.5° baseline at the Chicago shoreline. The tetroons were towed to 300 m by pibals. Azimuth and elevation angles were recorded every 30 s to 0.1° resolution. Two-way radio communication assured accurate timing coordination of the readings. The double theodolite pibal program of Biggs (1962) was used to obtain x , y , z positions (in shoreline coordinates) and compute u , v , w velocities at 30-s intervals. A three-point smoother was applied to the input data. Two sets of heights were obtained for each reading. The mean values of the two z s are plotted in the figures.

Figures 19 and 20 show the xz and xy plots of the tetroon launched from the shoreline near CLS at 0900 CST on August 12, about 60 min after lake-breeze onset. A nearly helical trajectory is found. After release from the tow balloons at 300 m, the tetroon moved inland in the inflow, slowly rising until reaching the convergence zone some 4 km inland. It entered into the main updraft of the convergence zone, showing 5-min mean ascent rates of up to 64 cm/s, similar to those computed earlier. The tetroon

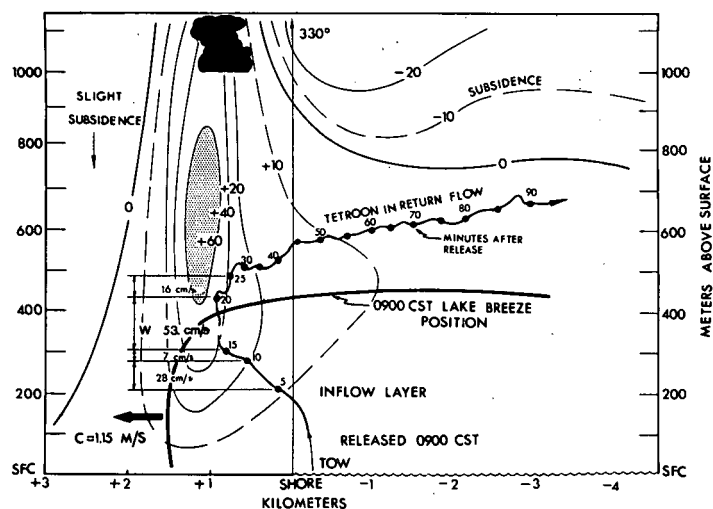


FIGURE 21.—Observed tetron track and isopleths of computed vertical motion (from pibal data) for lake breeze of Aug. 13, 1967. Computed updrafts greater than 60 cm/s are shaded. Mean 5-min vertical motions from tetron are shown. The clouds over the lake-breeze front are outlined.

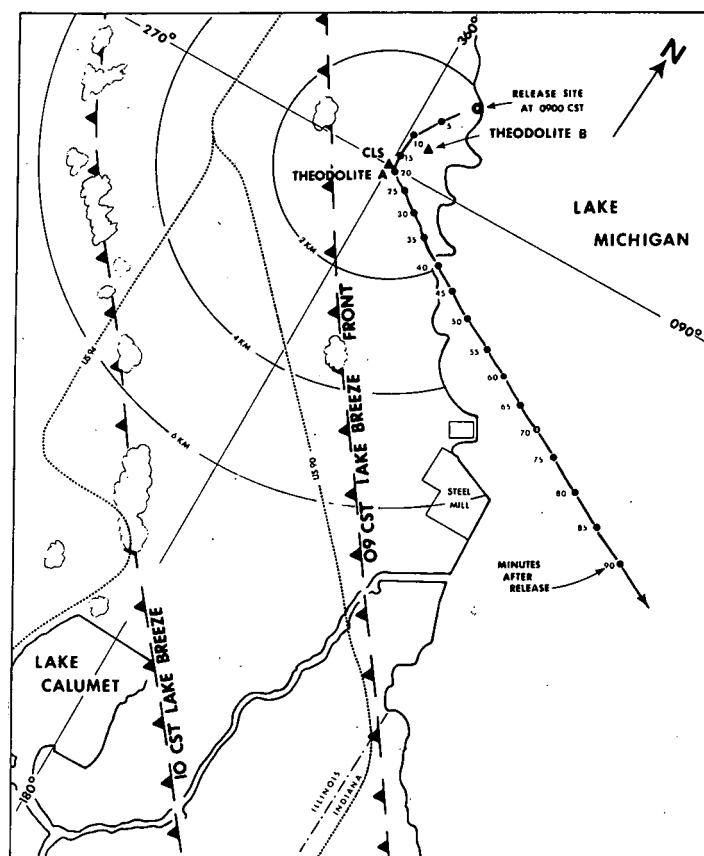


FIGURE 22.—Plan trajectory of tetron launched from Chicago shoreline at 0900 cst, Aug. 13, 1967.

rose out of the inflow layer just ahead of a cloud (fig. 9) and advected lakeward in the return flow at around 1000 m.

The balloon drifted about 2 km offshore before suddenly hitting a region of strong downward motion, where subsidence of over 50 cm/s was measured. The measured winds from the sinking tetron compare well with an earlier CLS pibal (fig. 19). On the return leg, the tetron sank back to 300 m and, after traveling several kilometers inland, began to experience considerable turbulence. As it approached the Lake Calumet area, it suddenly ascended to over 600 m, probably caught in a columnar thermal rising out of the deepening superadiabatic layer. Either the thermal itself collapsed, or the balloon "fell out" of this updraft; in any case, it descended to near its neutral level again before being lost in smoke and haze, almost 2.5 hr after launch. This thermal was probably unable to penetrate the remaining stable layer near the top of the deep inflow layer, as evidenced by the fact that at 1130 cst, the cloud band was several kilometers farther west. Thus, from this Lagrangian frame of reference, we see that air (and pollutants) leaving the shoreline near CLS would have completed at least one full cycle by noon, ending up in a locale quite different from that expected from analysis of surface wind data alone.

Figure 20 is a plot of the xy (horizontal) track of the tetron released at 0900 cst on August 12. It shows the two tracking sites and the release point. The tetron was gently drifting southeastward down the shoreline while it was performing its in, out, up, down, and in again routine in the zz plane. It is curious to note that, particularly in the first 90 min of flight, there was a tendency for the tetron's trajectory to curve slightly to the right. This could very well be the influence of the Coriolis acceleration. Angell and Pack (1965) likewise detected a similar phenomena in their Atlantic City study.

The same type of analyses were performed on the pibal and tetron data taken on August 13. The tetron was

released from the same position at 0900 cst and, likewise, drifted inland and rose in the updraft zone with peak speeds in excess of 50 cm/s. As seen from the combined Eulerian and Lagrangian data plotted in figure 21, the agreement is again surprisingly close between the two techniques. On this occasion, dense smoke caused one of the theodolite operators to lose track of the tetron after the tetron had penetrated well offshore (at about 95 min). The xy plot of this tetron is shown in figure 22. The second observer, however, continued to track the tetron for about another 1 hr and his observations would indicate that the tetron did indeed sink offshore and return inland in the upper portion of the inflow layer.

Thus, optically tracked tetroons appear to be a most valuable tool in studying mesoscale air motions in all but the most heavily smoke-laden urban atmospheres. Continuing studies of tetroons released into lake breezes in the Milwaukee area during the summer of 1972 revealed air motions much the same as in the Chicago area. These results will be published in an upcoming paper.

6. AIRCRAFT MEASUREMENTS OF AEROSOL PATTERNS

It seems probable that suspended particulates having very low terminal velocities would follow trajectories in the lake-breeze cell similar to those discussed in the last section. However, to test this hypothesis, one must make aerosol concentration measurements. Standard devices such as high-volume samplers are generally employed only

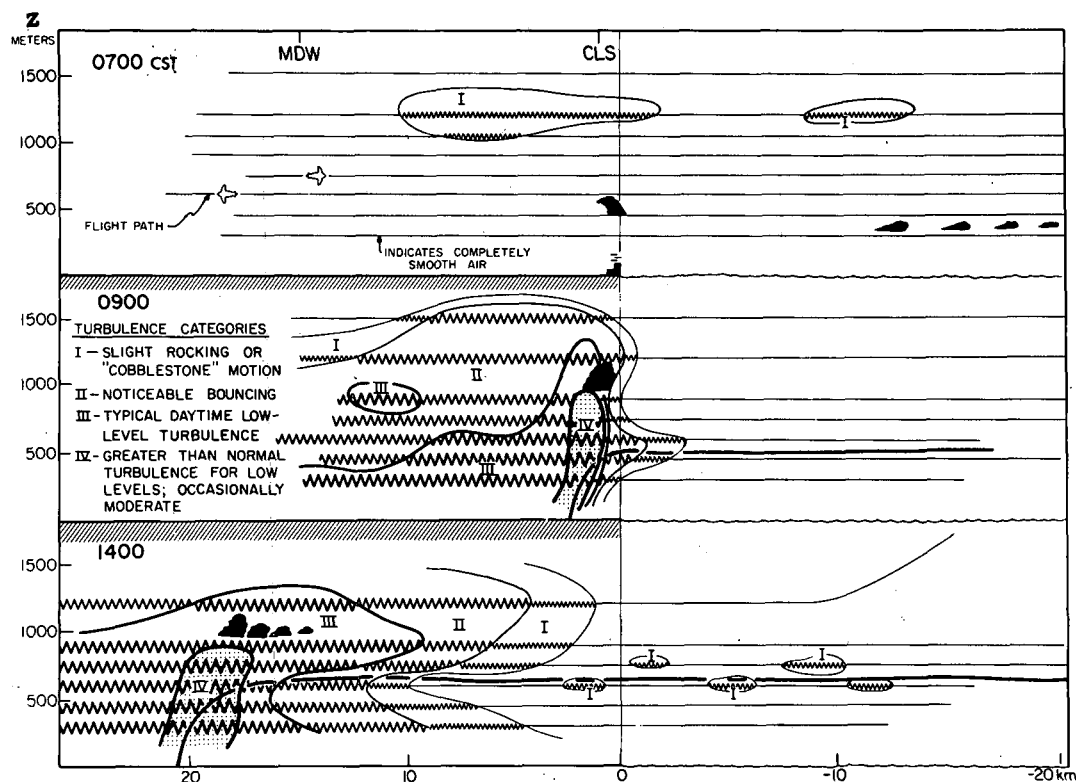


FIGURE 23.—Flight altitudes for aerosol sampling flight on Aug. 13, 1967, made by NCAR Queen Air through Chicago lake breeze. Turbulence, as noted by an observer onboard, is plotted according to the categories listed. The boundary of the lake breeze is given by a heavy line. The clouds above the front are outlined.

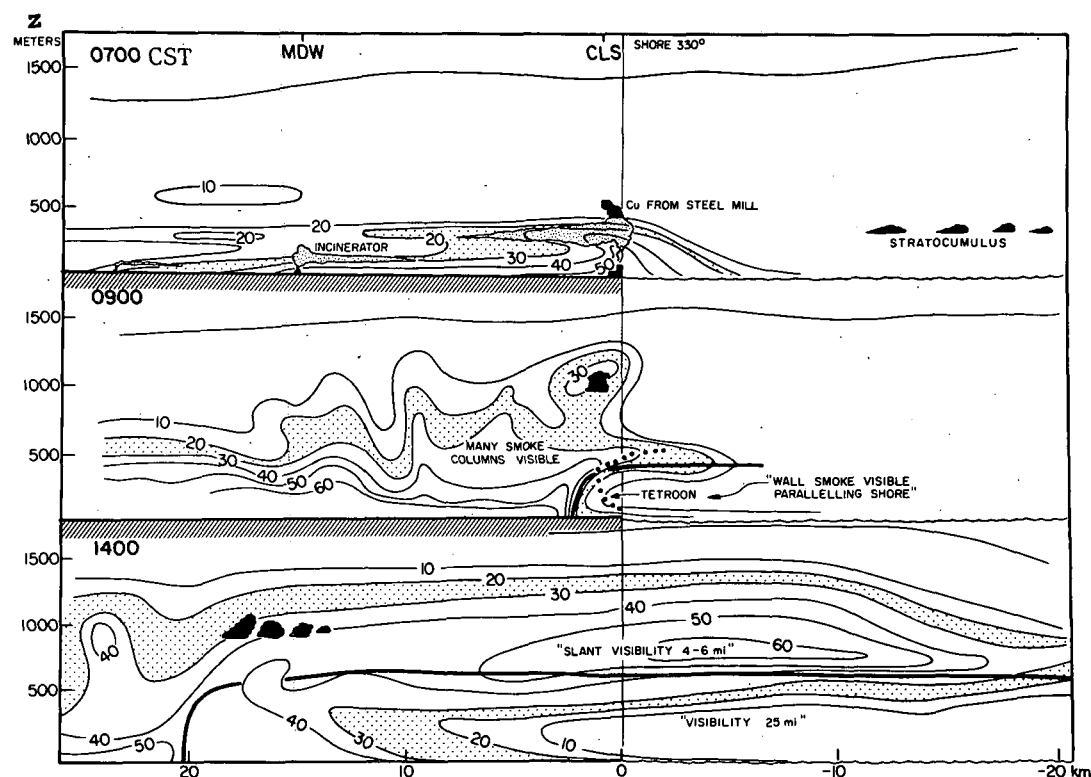


FIGURE 24.—Cross sections of the aerosol concentration in the 0.5- to 3.0- μm size range during the Chicago lake breeze of Aug. 13, 1967. Isoleths are drawn every $10 \times 10^6 \text{ m}^{-3}$ with the interval from 20 to $30 \times 10^6 \text{ m}^{-3}$ stippled.

at ground installations, have averaging times far too long to discriminate the rapid changes that occur, and cannot count particulates according to size class. This, then, appears to be an ideal application for the newer optical particle sensors, which can be mounted on an aircraft.

Fortunately, on August 13 an instrumented NCAR Queen Air aircraft was available for such measurements. A light-scattering aerosol instrument counted suspended particulates and sized them into the following size ranges: 0.5-3.0, 3-5, 5-7, and 7-9 μm . The instrument has a time

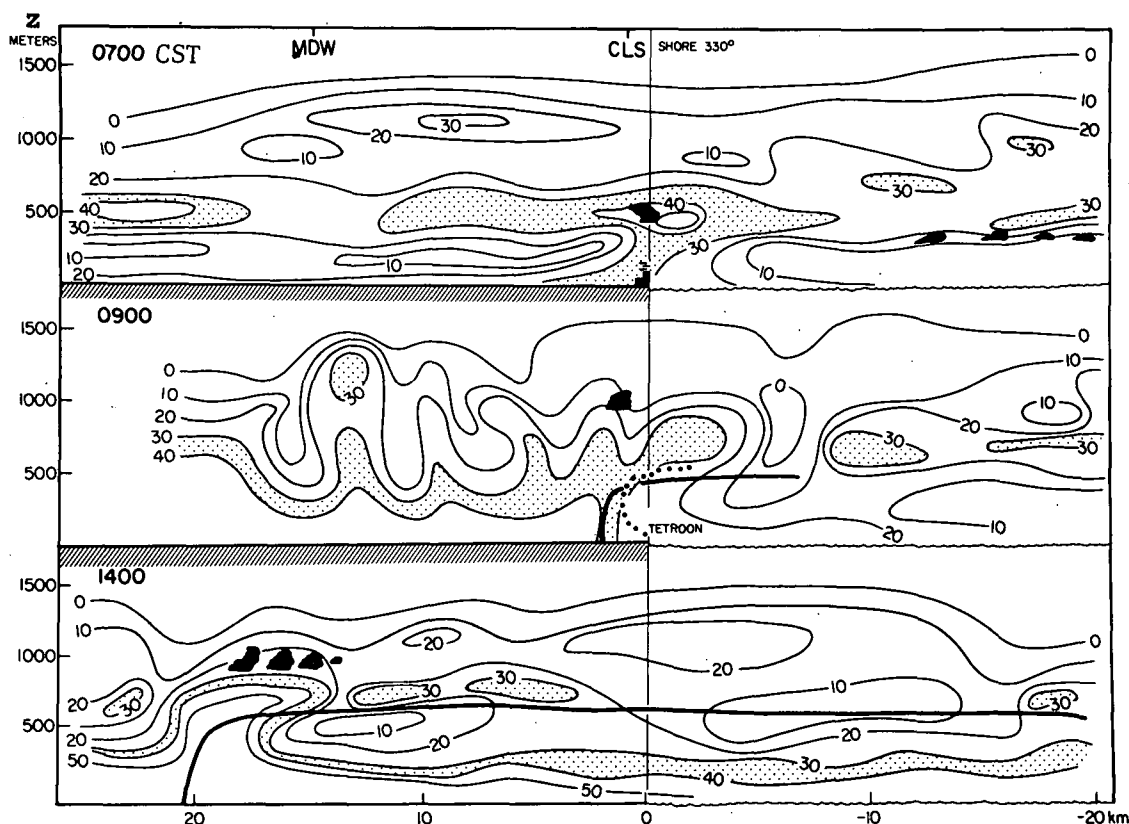


FIGURE 25.—Same as figure 24 for particles in the 7- to 9- μ m size range. Interval from 30 to $40 \times 10^2 \text{ m}^{-3}$ stippled.

constant of 0.25 s. A reverse flow temperature probe (with a nominal 0.1 s time constant) was also used. In general, readings were made at 15- or 30-s intervals. The ground speed was maintained at a constant 120 kt, resulting in a data point every $\frac{1}{2}$ or 1 n.mi. Figure 23 shows the levels at which the traverses were made (generally 500-ft intervals) and the ground track of the plane is included in figure 8B. The flight was made in three segments: (1) early morning (representing nocturnal conditions); (2) during lake-breeze onset (when penetrative convection over land was clearly evident from the visible smoke columns), and (3) midafternoon (when the circulation cell had become well established). For the last two sets of data, all data were plotted with respect to base times of 0900 and 1400 cstr, and points were shifted corresponding to the inland penetration speed of the front.

The various features of the lake breeze are strikingly illustrated by the aerosol concentration cross sections (figs. 24, 25). For particles in the 0.5- to 3.0- μ m size range, terminal velocities range from approximately 0.01 to 0.1 cm/s. In effect, they drift with the air motions. At 0700 cstr (fig. 24), the smallest particles (probably what could be called "smoke") were clearly stratified near the surface. Smoke from various incinerators and industries drifted shoreward in the land breeze, and apparently rose in a broad area of upward motion from the combined city heat-island and offshore convergence zone of the land breeze. It then returned aloft in the northeasterly winds above 300 m. Areal photographs clearly showed a dense smoke layer above 300 m about 20 km west of the city at sunrise (fig. 7). By 0900 cstr, stirring of the dense low-level pollution layer by penetrative convection over land

became evident. Most notable was the smoke that was forced high over the convergence zone, where the aerosol gradient clearly coincided with the visible wall of smoke paralleling the shore. A narrow tongue of smoke was also photographed extending lakeward at 600 m in the return flow—precisely the trajectory suggested by the tetroon. By 1400 cstr, the return flow was completely filled with smoke for over 20 km offshore. These small particulates were also descending into the upper third of the inflow layer over the lake. The underlying clean air moved onshore in the lower two-thirds of the inflow layer and quickly became polluted throughout the depth of the inflow after 3–5 km of inland fetch due to fumigation from the upper portion of the inflow layer, as well as from additional input from city sources. The fact that the "smoky air" did not descend more than a third of the way into the onshore flow layer is important. This explains the relatively clean air at the surface near the shoreline (remember the SO_2 traces in figs. 8A, 8B).

Figure 26 is a graphic illustration of this pattern, showing clean air near the surface advecting onshore, but capped with dense pollutants in the upper portion of the inflow. A plot of a potential temperature cross-section at 1400 cstr (fig. 27) clearly reveals that the top of a turbulent internal boundary layer (TIBL) intersects the murky air capping the inflow some 3–5 km inland. This causes continuous fumigation of pollutants to the surface in this zone, and the clear zone shown in figure 26 promptly disappears. We would expect high surface concentrations of various pollutants to be found beginning several kilometers inland. Indeed, at the SO_2 monitor at TAM Station No. 6 (fig. 8B), levels do not fall with the passage

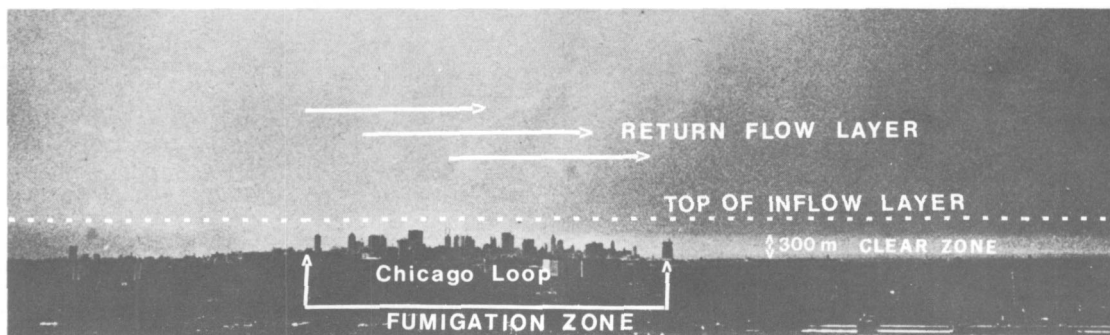


FIGURE 26.—View toward the Chicago Loop (CGX) from CLS at 1400 cst, Aug. 13, 1967. The clear zone in the lower portion of inflow layer disappears due to fumigation of pollutants from aloft about 3–5 km inland.

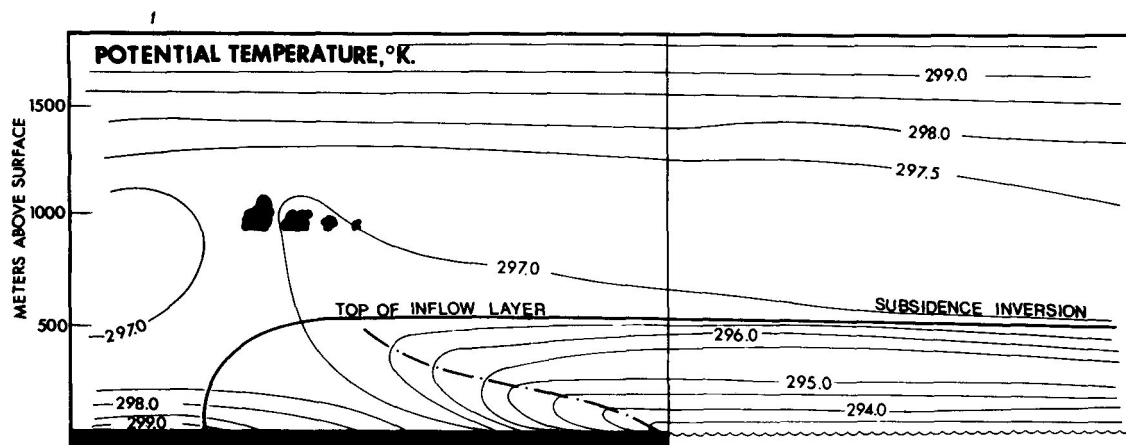


FIGURE 27.—Isopleths of potential temperature derived from observations taken by NCAR Queen Air, data centered on 1400 cst, Aug. 13, 1967. The top of the TIBL is indicated by broken line.

of the lake-breeze front. They continue relatively high through the afternoon, most likely from the downward fumigation of plumes from refinery operations upwind near the shoreline. This particular station frequently reads very high values during afternoons when lake breezes are in progress. The fumigation phenomena is discussed in great detail by Lyons and Cole (1973).

The largest particles (7–9 μm) for which cross sections were made have fall speeds around 1–2 cm/s. This is sufficient to produce a noticeable size sorting of aerosols in the circulation cell. Changing from a rather stratified pattern in early morning, the isopleths become more distorted by 0900 cst (fig. 25). By 1400 cst, high concentrations of these particles were found being supported in the updraft of the convergence zone. Over the lake, however, the highest numbers of large particles were found near the surface, having fallen out of the slowly subsiding return flow air.

7. THERMAL STRUCTURE OF A LAKE BREEZE

The analysis of potential temperature at 1400 cst on August 13 (fig. 27), on a scale corresponding to figures 24 and 25, was obtained by combining temperature measurements from the aircraft, those from the surface hygrometeorological tower at ANL. Several ship reports over water are also included. A number of distinct features are apparent. The packing of the isentropes above 1300 m corresponds

to the macroscale subsidence inversion associated with the high-pressure system dominating the Great Lakes area. Though becoming slightly elevated during the day, it remained unchanged through the observation period. Inland, west of the lake-breeze front, one finds a well-developed superadiabatic layer near the surface and roughly neutral conditions up to the 1300-m level. Convection inland remained dry due to the low surface dew-point values. In the lake-breeze inflow over water, two regions of isentropic packing are noted. The upper one corresponds to the mesoscale subsidence inversion of the lake breeze and the lower one is a very weak conduction inversion.

The increase in height of the internal boundary layer over land is pronounced (dashed line marks the top of the TIBL). The capping inversion is not completely eroded away until just a few kilometers before the convergence zone is reached. Though thermals originate from the heated ground layer, they probably do not penetrate into the return flow region except near the front. The observed cloud pattern tends to confirm this. The return flow layer itself is almost isentropic. This is a result of the fact that the air being lifted aloft from inland areas and that venting near the front from the inflow layer both have near constant potential temperatures of 297°K.

Turbulence was recorded during the flight using the SOTF (seat-of-the-pants) technique, qualitatively characterizing it into the five categories shown in figure 23 (smooth line indicating no turbulence at all). The plotted

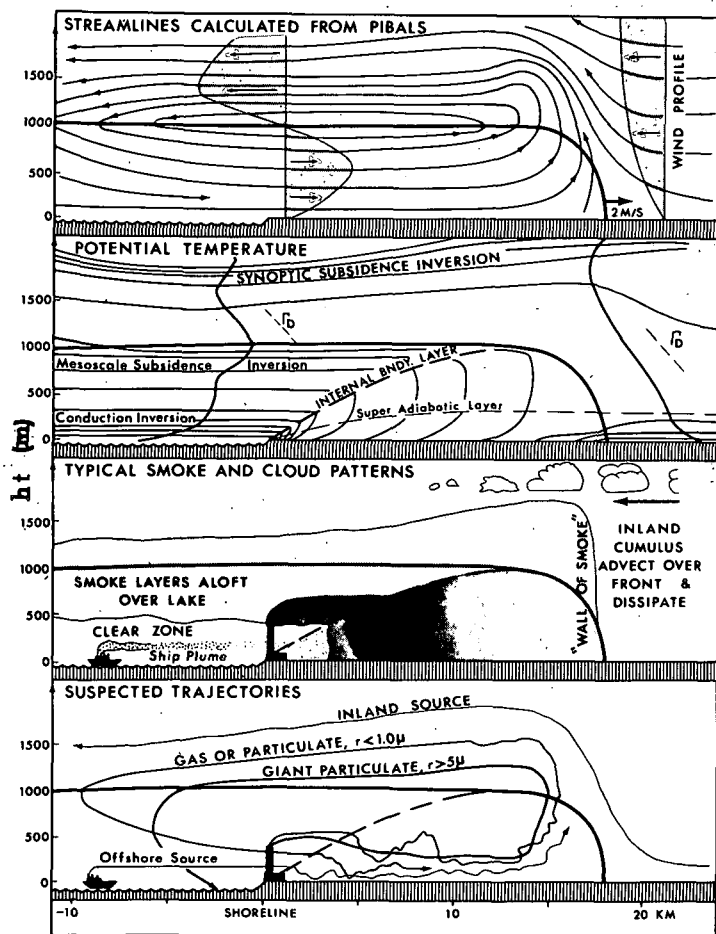


FIGURE 28.—Summary of the (A) streamline, (B) potential temperature, (C) smoke and cloud, and (D) trajectory patterns associated with the typical lake breeze.

turbulence reports (fig. 23) show several features. First, throughout the day, very light turbulence was occasionally generated within the stable layers of both the macroscale and mesoscale subsidence inversions. But the significant turbulence, composed to a large extent of dry penetrative convection, was found only over the heated land during the day. At 1400 CST, the turbulent inland air is being advected toward the lake in the return flow, but it has been separated from its source region (the superadiabatic layer) near the surface by the inflow of the lake breeze. The turbulence gradually decays after about 15 km. This explains why the plumes of smoke in the return flow layer over the lake appear to be so clearly layered. The buildup of turbulence beneath the TIBL can also be clearly seen at 1400 CST.

8. CONCLUSIONS

The air pollution meteorologist is often faced with a problem similar to that encountered by the local National Weather Service forecaster. He has at his disposal considerable data and forecasts pertinent to the large-scale structure of the atmosphere. However, it is the unknown mesoscale perturbations upon the general flow that can result in extreme deviations from the norm and doom his attempts at prediction and warning to failure. In this

paper, we have shown that Lake Michigan during the warm season causes extreme mesoscale disturbances in temperature and wind fields, often with highly adverse effects upon air quality. A local lake-breeze regime, with its associated phenomena of reduced mixing depths, recirculation, and fumigation, though poorly resolved by the operational data network, can still cover relatively large and often heavily populated areas.

Figure 28 summarizes the various features associated with a typical lake breeze. The generalized streamlines of a well-developed circulation cell (fig. 28A) are shown for a lake-breeze cell that has penetrated 15–20 km inland by midafternoon. Potential temperature patterns (fig. 28B) usually reveal three inversion surfaces over the lake. The highest is a slightly depressed synoptic scale subsidence inversion. A mesoscale subsidence inversion is found near the top of the inflow layer, overlying a surface-based conduction inversion, the strength of which depends on the air-water temperature contrasts. Over land, inland from the lake breeze, we typically find a surface-based superadiabatic layer with nearly neutral conditions extending upward to the top of the mixing layer (generally 1300–1800 m by midafternoon). Obviously, good dispersion conditions are present inland of the lake breeze. In the overland portion of the inflow, rapid remodification of the cool lake air occurs, with a shallow surface superadiabatic layer forming almost immediately upon landfall, and an ever deepening turbulent thermal internal boundary layer extends upwards, largely eliminating the capping stable layer at the top of the inflow after some 10–15 km inland (Bierly 1968). Thus, over land within the lake-breeze cell, mixing depths are considerably reduced but greatly variable, and are eminently favorable for day-long continuous fumigation of pollutants. As for the smoke patterns observed with well-developed lake breezes, they are sketched in figure 28C. Frequently, a wall of smoke marks the inland-rushing wind shift line.

Even more pronounced is the layer of smoke in the return flow and the upper portions of the inflow. Usually, one finds relatively clean air near the surface, though thin layers of smoke, from large lake steamers, frequently are seen near the water surface. Air near the surface within a few kilometers of the lakefront might be relatively pollution free, but, as shown, it is quickly dirtied by addition of new pollutants and, especially, downward fumigation. If the tetraon and aerosol data have been interpreted correctly, then the trajectories of gases and various size aerosols probably resemble those shown in figure 28D. Localities within the lake-breeze inflow, while protected from sources landward of the wind shift line (generally minimal in the Chicago area) find themselves in a situation analogous to being locked in a closed room with a fan running. While the largest particles probably fall out of the cell while over the water, an unknown fraction of the gases and small aerosols continuously recirculate during the day, causing ever increasing pollutant loading of the atmosphere within the inflow. The unanswered questions of greatest concern now are to determine what fraction of gases and various size particulates actually are recirculated within the cell.

The use of radiosonde data from up to 400 km away as representative of Chicago shoreline conditions is shown to be clearly inadvisable during such situations. The Environmental Meteorological Support Unit radiosonde established in Chicago for air pollution forecasting is located at Midway Airport, about 15 km inland. Even these soundings may not always detect lake breezes, 60 percent of which fail to reach the airport yet cover the heavily industrialized and populated shoreline areas.

With the high density of vehicular traffic and power plants along the shoreline, an ample supply of the primary pollutants (hydrocarbons and oxides of nitrogen) for photochemical smog production are available. This factor, combined with relatively warm temperatures, limited mixing depths, and increased insolation due to the suppression of cumulus activity near the shorelines, points towards a potentially serious problem for Chicago and other Great Lake cities. Thus, increased monitoring of oxidant levels would be advised in affected communities.

We feel that the above findings apply in a general way to other cities on the Great Lakes, such as Cleveland, Ohio, Buffalo, N.Y., and Milwaukee, Wis. A concerted effort is now underway in Milwaukee to take further observations using instrumented aircraft, serial pibal networks, optically tracked tetroons (some launched from offshore), and instrumented mobile vans specifically tracking fumigation from major elevated-point SO₂ sources on the lakefront. The impacts of these studies should bear heavily on major planning decisions such as the location of shoreline freeways and offshore airports, and wet cooling tower installation in areas affected by lake breezes. A preliminary study of the general ecological factors to be considered has been published by Lyons and Cole (1972).

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